# GNSS Precise Positioning Algorithms for Long-Distance/High-Altitude Vehicle Applications

Toshiaki Tsujii
JST Fellow at the University of New South Wales, Australia
(February 2000 – January 2002)

Supervisor : Prof. C. Rizos
School of Surveying and Spatial Information Systems, UNSW,
Sydney, Australia

# CONTENTS

## ACKNOWLEDGMENTS

Special gratitude is expressed to Prof. Chris Rizos, School of Surveying & Spatial Information Systems, UNSW, not only for serving as my supervising professor during my studies, but also for professional guidance, advice, and encouragement. Thanks, also, are extended to the co-authors of my papers, Dr. Jinling Wang, Dr. Linlin Ge, Dr. Joel Barnes, Dr. Craig Roberts, Mr. Liwen Dai, and Mr. Michael Moore.

Thanks are also due to all members of the Satellite Navigation and Positioning group (SNAP) of the School of Surveying & Spatial Information Systems, UNSW, for their assistance and hospitality. I will never forget the wonderful people of the SNAP group and my enjoyable stay in Sydney.

Finally, I would like to acknowledge the support from the Japan Science and Technology Corporation (JST) postdoctoral fellowship scheme which made this all possible.

Toshiaki Tsujii
February 2002
Sydney, Australia

## SUPERVISOR'S COMMENTS

I had the pleasure of hosting Dr. Toshiaki Tsujii within my research group, here at the University of New South Wales, for the period February 2000 to January 2002. Toshiaki was easily integrated within the activities of the Satellite Navigation and Positioning group (both technical and social!), and he was able to make valuable contributions. During this period a fruitful collaboration was established between Dr. Tsujii and several of my colleagues, in areas as diverse as tropospheric delay modelling, kinematic GPS/GLONASS positioning algorithms, and pseudolite research. I look forward to continuing this collaboration with Dr. Tsujii's return to the National Aerospace Laboratory.

Chris Rizos
February 2002
Sydney, Australia

## ABSTRACT

The algorithms for GNSS (Global Navigation Satellite System) precise positioning that have been developed by the author are reported in this report. These investigations have been carried out during the author's secondment to the SNAP (Satellite Navigation and Positioning) group, at the University of New South Wales, Australia, as a JST (Japan Science and Technology Corporation) fellow. The algorithms to process the measurements made on the signals of the GLONASS satellites have been developed to augment the GPS-based systems. The tropospheric delay error is one of the most critical error sources for long-distance & high-altitude vehicle positioning applications. Several methods to mitigate the tropospheric delay error have been developed and evaluated using flight data of an aircraft. In addition, a navigation/positioning service based on pseudolites installed on stratospheric airships was proposed. In this high-altitude airship application, the generation of the 'precise ephemeris' is one of the most important technical challenges. The 'inverted GPS' method has been developed and the preliminary experiments have shown excellent positioning stability in the static mode.


## GLONASS IMPLEMENTATION

The benefits of the combined use of the GLONASS and GPS navigation satellite constellations have become obvious for applications such as open-cut mining operations and highly dynamic vehicles such as spaceplanes. Moreover, using GLONASS satellites, in addition to GPS, is useful for long baseline applications since it increases the numbers of satellites in common view. Japan's National Aerospace Laboratory (NAL) conducted a kinematic GPS/GLONASS flight test for a feasibility study of spaceplane landing systems and the precise navigation of stratospheric airships. NAL has been developing its own Kinematic GPS Software (KINGS), and this was modified to process GLONASS data. The performance of this software was then evaluated using flight test data. The main objectives of this study were:

1) Evaluation of the accuracy of L1 single-frequency kinematic GPS/GLONASS positioning against GPS L1/L2 dual-frequency derived profile.
2) Performance evaluation of instantaneous GPS/GLONASS ambiguity resolution on-the-fly (OTF), using the LAMBDA method.

The following conclusions can be drawn from the results of the test:

1) The positioning accuracy of kinematic GPS/GLONASS is similar to that of kinematic GPS.
2) The instantaneous OTF performance of GPS/GLONASS with a mask angle of 30 degrees is similar to that of GPS with a mask angle of 10 degrees.

The second conclusion has important implications not only for highly dynamic aerospace vehicles but also for high-altitude or long-range kinematic applications, since using GPS and GLONASS increases the number of satellites in common view.

Details in :

TSUJII, T., HARIGAE, M., INAGAKI, T., and KANAI, T., (2000), Flight tests of GPS/GLONASS precise positioning versus dual frequency KGPS profile, *Earth Planets Space*, Vol. 52 (No. 10), pp. 825-829.

# TROPOSPHERIC DELAY ERROR MITIGATION

## A New Functional Model for the High-Altitude Vehicle

The residual tropospheric delay in GPS carrier phase observations is one of the most significant error sources for precise kinematic (as well as static) applications. Many investigators have proposed error mitigation techniques using ground-based GPS reference receiver networks. These techniques appear to be well suited for both static surveying and mobile vehicle positioning, on the ground. The typical mitigation strategy is to estimate the effect of the residual delay on the user receiver by interpolating the delay determined at a number of GPS reference receivers. However, because the tropospheric delay depends on receiver altitude, this technique is effective only when all receivers (including the user receiver) are located at a similar height. The use of tropospheric delay models also has its problems, as on-the-fly ambiguity resolution becomes critical in such circumstances. Therefore, these techniques may not be feasible for precise positioning of high-altitude receiver platforms.

A new functional model for the residual tropospheric delay has been proposed which is explicitly height-dependent. The effectiveness of this new model for the precise positioning of high-altitude vehicles has been demonstrated. Depending on the type of meteorological sensors installed at/on the ground/airborne sites and their accuracies, it would be possible to choose the appropriate physical parameter to be estimated. This feature will be useful for the Japanese stratosphere airship application, and for deciding which type of sensors for earth environment research will be installed.

Details in :

TSUJII, T., WANG, J., RIZOS, C., HARIGAE, M., & INAGAKI, T., (2000), Estimation of residual tropospheric delay for high-altitude vehicles: Towards precise positioning of a stratosphere airship, *13th Int. Tech. Meeting of the Satellite Division of the U.S. Inst. of Navigation*, Salt Lake City, Utah, 19-22 September, 696-704.

## Computation of Tropospheric Delay by Using External Data

For the precise positioning of the HAPS (High Altitude Platforms System), the residual tropospheric delay in GPS carrier phase observations is one of the most significant error sources. Tsujii et al (2000) has proposed a new functional model for the residual tropospheric delay which is explicitly height-dependent, and demonstrated the effectiveness of the model for the precise positioning of the HAPS in cases where the ambiguities were resolved beforehand. However, it is difficult to estimate the tropospheric delay simultaneously with the ambiguities and coordinates in the kinematic mode, contrary to the case for static GPS applications. This is mainly due to the lack of suitable visible satellites since only low elevation satellites have the observability for the estimation of the tropospheric delay.

The tropospheric delay was estimated using four kinds of datasets/models:

1) a global tropospheric model,
2) grid point values from a numerical weather model,
3) surface meteorological measurements and the lapse rates of temperature and water vapour pressure estimated using regional/temporal meteorological data, and
4) meteorological data measured at the high-altitude vehicle and the zenith total delay estimated from a ground GPS network.

The performance of the four techniques (to mitigate the tropospheric delay error for the precise positioning of the HAPS) was evaluated using aircraft flight data. The following conclusions can be drawn:

1) The use of the global tropospheric delay model may not be adequate for the precise positioning of the HAPS.
2) The GPV of NWM reduces the residual tropospheric delay error significantly compared with the global model. The GPV data can easily be obtained from JMBSC, therefore the user does not need to measure and process meteorological data. Also, the forecast data would be useful for real-time positioning. In future work, the denser and more frequent GPV data (a 10km mesh data, available every hour) will be used. The ray-tracing method to compute the tropospheric delay for the individual satellite would be promising because a mapping function is not necessary, and therefore the method may not be erroneous in the situation where the tropospheric delay differs directionally.
3) The use of surface meteorological measurements can mitigate the tropospheric delay error. However, it is recommended that the lapse rates of the temperature and the water vapour pressure are estimated from the regional radiosonde data, because the two-parameter formula (Askne & Nordius, 1987) used to compute the tropospheric delay at the aircraft is very sensitive to these values.
4) The technique of using the ADS data at the aircraft, and the ZTD values estimated from the processing of a ground GPS network, seems to be the best among the four methods evaluated. However, it should be investigated further in order to evaluate the effectiveness of the humidity measurements at the aircraft, because the humidity was not measured in this experiment. Furthermore, an experiment using the absolute ZTD estimated from a larger GPS network will be conducted.

Details in :

TSUJII, T., WANG, J., RIZOS, C., DAI, L., HARIGAE, M., INAGAKI, T., FUJIWARA, T., & KATO, T., (2001), A technique for precise positioning of High

Altitude Paltforms System (HAPS) using a GPS ground reference network, *14th Int. Tech. Meeting of the Satellite Division of the U.S. Inst. of Navigation*, Salt Lake City, Utah, 11-14 September, in proc.

## A NAVIGATION/POSITIONING SERVICE BASED ON PSEUDOLITE INSTALLED ON STRATOSPHERIC AIRSHIPS

Recently some countries have begun conducting feasibility studies and R&D projects on High Altitude Platforms Systems (HAPS). Japan has been investigating the use of an airship system that will function as a stratospheric platform (altitude of about 20km) for applications such as environmental monitoring, communications and broadcasting. It is planned that such an airship network would cover all of Japan. Remote sensing from such an airship would be very effective because it floats above the same ground area, permitting continuous monitoring of the surface. However, the precise positioning of the airship is one of the most important technical challenges for such a project. If pseudolites (PL) were mounted on the airships, their GPS-like signals would be stable augmentations that would improve the accuracy, availability, and integrity of GPS-based positioning systems. The accuracy of the pseudolite positions would be a limiting factor for such a service since the PL 'ephemeris error' is more serious than GPS due to the lower height of the airship.

A conceptual design for an airship-based augmentation system was proposed, and some schemes for estimating the pseudolite position were investigated. Although precise positioning using 'GPS transceivers' seems to be the best method, the inverted-GPS approach was investigated in a preliminary feasibility study. The static test showed excellent positioning stability (standard deviations less than 5mm), while the kinematic test suggested the need to investigate further the mitigation of residual errors such as multipath, phase polarization, and antenna phase centre variation.

Details in :

TSUJII, T., RIZOS, C., WANG, J., DAI, L., ROBERTS, C., & HARIGAE, M., (2001), A navigation/positioning service based on pseudolites installed on stratospheric airships, *5th Int. Symp. on Satellite Navigation Technology & Applications*, Canberra, Australia, 24-27 July, paper 49, CD-ROM proc.

TSUJII, T., RIZOS, C., WANG, J., DAI, L., & HARIGAE, M., (2002), A navigation/positioning service based on pseudolites installed on stratospheric airships, *Journal of the Japan Society for Aeronautical and Space Sciences*, Vol. 50, No. 576, pp. 36-39. (in Japanese).

## FUTURE WORK

The algorithms for tropospheric delay error mitigation developed by the author will be implemented within NAL's vehicle navigation/positioning systems. The use of numerical weather forecast models will be further investigated because this method is suitable for real time operation. The ray-tracing method to compute the tropospheric delay for the individual satellite is a promising approach because a mapping function is not necessary. Hence the method may not be erroneous in situations where the tropospheric delay differs directionally. Future collaborative work with the SNAP group using these techniques will be conducted for the development of an InSAR-GPS integrated remote sensing system.

A number of feasibility studies and experiments of pseudolite(PL)/GPS systems will be conducted in order to develop a feasible airship-based navigation/positioning system. In order to track the PL signal robustly, and to mitigate the multipath error, the modification of the GPS receiver firmware, and ultimately the development of a 'software receiver', will be necessary. It is intended that collaborative work with the SNAP group will continue in this research area. The legal issue of using the GPS radio frequency for signal transmissions should be investigated if an operational PL/GPS service becomes feasible. Such research will be extended to establish local-area precise positioning systems such as for indoor GPS applications, the planetary rover guidance system, and spacecraft formation flight systems.

## LIST OF PAPERS

### Journal publications

TSUJII, T., RIZOS, C., WANG, J., DAI, L., & HARIGAE, M., (2002), A navigation / positioning service based on pseudolites installed on stratospheric airships, *Journal of the Japan Society for Aeronautical and Space Sciences*, Vol. 50, No. 576, pp. 36-39. (In Japanese)

WANG, J., TSUJII, T., RIZOS, C., DAI, L., & MOORE, M., (2001), GPS and pseudo - satellites integration for precise positioning, *Geomatics Research Australasia*, 74, 103-117.

TSUJII, T., HARIGAE, M., INAGAKI, T., and KANAI, T., (2000), Flight tests of GPS/GLONASS precise positioning versus dual frequency KGPS profile, *Earth Planets Space*, Vol. 52 (No. 10), pp. 825-829.

### Proceedings

TSUJII, T., RIZOS, C., WANG, J., DAI, L., ROBERTS, C., & HARIGAE, M., (2001), A navigation/positioning service based on pseudolites installed on stratospheric airships, *5th Int. Symp. on Satellite Navigation Technology & Applications*, Canberra, Australia, 24-27 July, paper 49, CD-ROM proc.

TSUJII, T., WANG, J., RIZOS, C., DAI, L., HARIGAE, M., INAGAKI, T., FUJIWARA, T., & KATO, T., (2001), A technique for precise positioning of High Altitude Paltforms System (HAPS) using a GPS ground reference network, *14th Int. Tech. Meeting of the Satellite Division of the U.S. Inst. of Navigation*, Salt Lake City, Utah, 11-14 September

DAI, L., WANG, J., TSUJII, T., & RIZOS, C., (2001), Pseudolite applications in positioning and navigation: Modelling and geometric analysis, *Int. Symp. on Kinematic Systems in Geodesy, Geomatics & Navigation (KIS2001)*, Banff, Canada, 5-8 June, 482-489.

DAI, L., WANG, J., TSUJII, T., & RIZOS, C., (2001), Pseudolite-based inverted positioning and its applications, *5th Int. Symp. on Satellite Navigation Technology & Applications*, Canberra, Australia, 24-27 July, paper 9, CD-ROM proc.

WANG, J., RIZOS, C., DAI, L., TSUJII, T., BARNES, J., GREJNER-BRZEZINSKA, D., & TOTH, C.K., (2001), Integration of GPS and pseudo-satellites: New concepts for precise positioning, *IAG Scientific Assembly*, Budapest, Hungary, 2-7 September

WANG, J., DAI, L., TSUJII, T., RIZOS, C., GREJNER-BRZEZINSKA, D., & TOTH, C.K., (2001), GPS/INS/Pseudolites: Concepts, simulation and testing, *14th Int. Tech. Meeting of the Satellite Division of the U.S. Inst. of Navigation*, Salt Lake City, Utah, 11-14 September

CHIKAZOE, H., TABEI, T., KUSABA, R. & TSUJII, T., (2001), Elongation of kinematic GPS survey by multiple baseline connection, *2001 Japan Earth and Planetary Science Joint Meeting*, Tokyo, Japan, 4 – 8 June (In Japanese)

CHIKAZOE, H., TABEI, T. & TSUJII, T., (2001), Long Range Kinematic GPS Survey – Improvement of Baseline Connection Method and the Impact of the SA-OFF, *96th Meeting of the Geodetic Society of Japan*, Sapporo, Japan, 15 – 17 October (In Japanese)

TSUJII, T., WANG, J., RIZOS, C., HARIGAE, M., & INAGAKI, T., (2000), Estimation of residual tropospheric delay for high-altitude vehicles: Towards precise positioning of a stratosphere airship, *13th Int. Tech. Meeting of the Satellite Division of the U.S. Inst. of Navigation*, Salt Lake City, Utah, 19-22 September, 696-704.

WANG, J., TSUJII, T., RIZOS, C., DAI, L., & MOORE, M., (2000), Integrating GPS and pseudolite signals for position and attitude determination: Theoretical analysis and experiment results, *13th Int. Tech. Meeting of the Satellite Division of the U.S. Inst. of Navigation*, Salt Lake City, Utah, 19-22 September, 2252-2262.